CONF-811006--1

LA-UR-81-899

MASTER

TITLE: SOIL LOSS AND LEACHING, HABITAT DESTRUCTION, LAND AND WATER DEMAND IN ENERGY-CROP MONOCULTURE: SOME QUANTITATIVE LIMITS

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SUBMITTED TO: INTERNATIONAL CONFERENCE ON ENERGY USE MANAGEMENT--III (WEST BERLIN, 26-30 OCTOBER 1981)

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INTRODUCTION

The environmental impacts of growing biomass for energy, especially for liquid automotive fuels, are potentially large. They are sensitive to the low power production per unit area (high land requirement) and to net energy balances. In this paper, I assemble initial quantitative estimates for impacts per unit power within several classes of impacts--and conversely, for limits to power produced if one avoids worst-class impacts. Four major types of biomass energy technologies are considered.

METHOD

Three classes of environmental impacts may be distinguished: (1) Irreversible but avoidable environmental degradations leading to losses in productivity bases, when steady-state renewal rates are exceeded. Examples include simple soil erosion and massive ecosystematic failures in clearing tropical wet forests. By "irreversibility," I mean loss for at least one human generation. Losses usually extend beyond potential energy productivity to include local agricultural productivity and even global genetic resources. (2) Increments in use of renewable environmental resources, requiring tradeoffs against current uses of these resources (land, water, etc.) or commitment of future reserve capacities. The finitude of renewal capacity, as o[illegible] l erosion tolerance,[1-3] limits power production from biomass. All resource [illegible] bear costs, which are either internalized by producers (added to product costs) or externa[illegible]zed to be borne by society as a whole, such as soil erosive losses. Externalized costs can be insidious and large, and merit intensive scrutiny. In any event, one must evaluate resource uses per unit of power produced. One mu[illegible] therefore know (a) yield of <u>raw</u> biomass energy per area (for land use) and per input (of water, e.g.), and (b) net energy balance in total production. The latter has been a source of controversy in ethanol production for "gasohol"[4-10] and it incorporates several subtleties. (3) Increments in use of nonrenewable resources, particularly fossil fuels and phosphorus reserves. These are not direct environmental impacts, but in "second order" they are required to support production of biomass and their depletion affects our ability to restore environments damaged by biomass production, such as P-depleted leached areas.

In all, I do not discuss the more abstract environmental values--aesthetics, recreation, and the like--which are hard to quantify but very important; I leave these for later work.

FOCUS ON SOME MAJOR IMPACTS: CLASSIFICATION AND INITIAL QUANTIFICATION

A. Class 1: "Irreversible" Impacts

1. Permanent agricultural/silvicultural productivity losses. In temperate zones where most industrial nations like the U. S. lie, the major threats are soil erosion and loss of tilth (organic matter important for aeration, water retention, cation-exchange capacity). Erosion is predictable quantitatively (cf. the Universal Soil Loss Equation[11]) and is a graded, noncatastrophic process. It can be tolerated in a steady state,[2,12] at a rate dependent upon local soil nature and climate, but recovery from time-integrated excesses is at a slow, geologic rate (100-10,000 years for full depth[13]). In the U. S., even our "advanced" agricultural practices exceed erosion tolerance limits over perhaps 2/3 of our food cropland![12,14] Some choices of energy crops are superior for minimizing erosive potential; the continuous cover provided by grasses and trees is preferred[15] over bare-soil periods attained with most annual crops.

In the wet tropics, clearing the rain forest for cropping herbaceous or non-native woody crops often leads to irreversible failures. In recent times, even enthusiasts for such schemes are reevaluating the ecological price.[16] The failure,[17-20] a loss of soil and nutrients and of regenerative capacity of the original ecosystem for up to several hundred years, is rapid and hard to reverse, once started. Contributing are several factors: (1) Fast erosion of bared soil in high-rainfall areas.[19-20] (2) Fast leaching of mineral nutrients to deep zones or groundwater, ordinarily prevented by tight biological recycling achieved by plants' woodiness and by dense root mats.[21-23] (3) Exacerbating the latter, a very low reserve of mineral nutrients.[19] (4) Low resilience of animal and plant species diversity, perhaps because slowly-reproducing "K-selected" species[18] evolve in the stable tropical forests. (5) Loss of recolonization ability,[24,25] including germination areas for seeds because bare soils are hotter. (6) Reduction of special microflora for nutrient recycling, microfloral species that are not supported in the monocultures replacing forests. In general, we lack knowledge of these component aspects.[26]

Loss of land productivity for many years after a few years' extraction of biomass energy gives a poorer power production per area of land used. Consider temperate crops yielding 20 tonnes per hectare of dry matter per year, as raw energy (before processing energy losses and debits for auxiliary energy inputs). Assume that productivity is lost for 100 years after 30 years' use. The power production is then

$$P = \frac{\text{energy}}{\text{time}} = \frac{(30\ \text{yr})(20\times10^{3}\ \text{kg ha}^{-1}\text{yr}^{-1})(18\times10^{6}\ \text{J kg}^{-1})}{(130\ \text{yr})(3.1\times10^{7}\ \text{s yr}^{-1})} = 2.7\ \text{kW ha}^{-1}\ ;$$

For a tropical crop yielding 50 tonnes ha^{-1} for 6 years with 100 years' subsequent loss, the rate is only 1.6 kW ha^{-1}. Compare these figures with one of the most land-intensive fossil-fuel production methods, the strip-mining of coal from a modest seam (5 m thick, 80% recoverable) with any given part of the mine tied up for 1 to 10 years. The power production is then

$$P = \frac{(0.80 \text{ recovery})(5\text{x}10^4 \text{ m}^3\text{ha}^{-1})(1.4\text{x}10^3\text{kg coal m}^{-3})(26\text{x}10^6 \text{ J kg}^{-1})}{(1 \text{ to } 10 \text{ yr})(3.1\text{x}10^7 \text{ s yr}^{-1})}$$

$$= 4.7 \text{ to } 47 \text{ MW ha}^{-1}$$

2. Gene-pool loss. Clearing whole ecosystems of native vegetation (and animals) contributes to extinction of wild plant species at a rate that is hard to quantify. Even in a narrow, economic sense, this is a loss of (1) potential new economic plants[27] not yet identified, and (2) genetic diversity[28] in relatives of existing crops, for interbreeding so that the latter keep pest resistance as pests co-adapt. Such breeding is necessary on a 10-to-20 year rotation, and many plant scientists see the need for expanding the pool of genes beyond our limited breeding stock. Once lost, the wild-plant gene pool is eternally lost. This may be the most severe impact of increased land use for biomass, yet the least understood and quantified.

3. Carbon dioxide addition to the atmosphere? Replacement of native plant communities by energy-crop or other monocultures (except perhaps by trees) may substantially decrease both standing biomass and soil organic matter.[29-36] The carbon content of the latter two reservoirs currently totals about twice[30,31,37] the atmosphere's carbon contained in CO_2. Consider a conversion of x per cent of average biomass on earth to energy crops with half the original biomass density. If half the injected CO_2 remains in the air, as apparently occurs[34] for fossil-fuel injection of CO_2, then this might contribute an 0.5 per cent increase in atmospheric CO_2.

The nature, degree, and negative implications of climatic changes[38-40] that might be induced by significantly increased CO_2 levels are being avidly researched and hotly debated today. Agriculture itself (including silviculture) may suffer strong negative impacts--the slight increase in growth rate[41,42] from CO_2 directly may not occur in open fields[30,41,43] and may be more than cancelled by shifts in rainfall zones.[38,39] In any event, CO_2 injection and subsequent climatic changes are reversible only by oceanic uptake over long times, 500 to 5000 years.[34,38,44] In our own interests, we might need to stay within a "tolerance" of a factor-of-two increase.

In contrast, fossil-fuel use contributes to atmospheric CO_2 continuously, in proportion to integrated energy rather than power. At 1/2 retention of CO_2 in air, the increase is about 5 parts per million (320 ppm is the current level) per 10^{21} J produced (world annual production is about 0.3×10^{21} J). Biomass use contributes only during initial land conversion and not during steady-state use--perhaps 26 ppm increase per 10^{21} J per year of added power.* However, it is much debated [29-36] if land conversion has clearly contributed to CO_2 increases historically.

B. Class 2: Effects of Using Renewable Environmental Resources.

1. Water use. Biomass energy production requires far more water per unit energy produced than any other technology. Even coal liquefaction, criticized for a high water use approximating two volumes water per volume of liquid fuel ($0.08\ m^3\ GJ^{-1}$), is beggared by biomass production requiring at least 600 to 2000 times greater use per unit energy. Much of this use is an added transpirational demand over that of the natural ground cover. Water use should be charged against biomass production whether water is drawn directly from managed water supplies via irrigation, or whether rainfall is diverted from aquifer recharge. The fractional commitment of water resources for biomass energy (raw, not even net) far exceeds the fractional contribution to energy supply, by a factor of perhaps 4 in the U. S.** Povich[45] has noted the strong constraint on biomass power capacity enforced by water availability. Note two large additional consequences for environmental quality: drying up large wild areas, as happened in the Owens Valley because of California water projects, and flooding of large catchment/impoundment areas to bring more water under human management.

2. Land use, within soil erosion tolerances. The calculational method of Sect. (A1) can be adapted here, dropping the extra span of time lost for regeneration. In the temperate-zone example, the power production becomes 11.5 kW ha^{-1}. Thus, if arable land constitutes 20% of total land area, the rate of committing our arable land exceeds by a factor of 1.3 the rate of satisfying our energy demand, assuming the latter is $80 \times 10^{18}\ J\ yr^{-1}$ or 2.6×10^{12} W. This factor is inflated by low net energy balance in biomass energy production (at least 2 to 10 J in as raw energy per J out) and by prior commitment of a

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*I assume that the same primary productivity is retained, and that the average distribution of biomass parallels that of productivity, which totals $3.1 \times 10^{21}\ J\ yr^{-1}$.

**I assume a low water use of $80\ m^3\ GJ^{-1}$, appropriate for only 5% of area as irrigated.

large fraction of land to agriculture. In the tropics, the factor is more favorable because power demand is lower in most tropical nations, but the sustained-yield area may also be notably lower as a fraction of total area.

The erosion tolerance is a crucial factor limiting the effective area for biomass production. The tolerance on marginal land, which land is often touted as a solution for areal limitations, is low.[46] Larson,[1] Tyner,[47] Roller et al.,[46] and others have discussed the limitation, to perhaps 1 or 2% of power demand in the U. S.

Land use, considered as a resource denial as a primary environmental effect, has consequent environmental effects such as reversible habitat destruction (of non-endangered species).

3. Air and water quality. In comparison to conventional energy technologies, biomass energy production rates rather well regarding air-quality impacts in production and end use.[7,8] NO_x and particulate emissions are comparable, SO_x emissions are lower. Water quality is more impacted, however, mostly because of salinization of surface water by irrigation demands and also nitrate loading of surface and groundwaters from incremental N-fertilizer use.[48] For lack of space here, I leave the topic for future discussion. Both human economic and ecosystematic losses are attributable to water-quality degradation.

C. Class 3: Effects of Using Nonrenewable Resource Reserves

Drawdown of soil nutrient reserves[49] by harvesting plant parts for processing elsewhere provides the main occasion for using nonrenewable resources, especially phosphorus. The redistribution of plant ash after fuel conversion is generally uneconomic, because of the low value of the nutrients vs. tractor fuel required for redistributing them. Phosphorus use is an essentially irreversible commitment without building up soil reserves, because it is soluble phosphorus forms that are in short supply in soil; applied phosphorus is soon transformed to insoluble forms,[45,50] and demand is continuous. Phosphorus demand provides a limitation on total biomass energy (not power) producible--see Povich.[45] Nitrogen demand is similar in consequences, though it acts by enforcing a requirement for fossil fuels in fertilizer production; I give no quantitative discussions here.

PRODUCTIVITY AND NET ENERGY BALANCE

Productivity per unit of land is low; only 0.5 to 3% of solar energy, itself diffuse, is fixed. Productivity per unit of water is also low. Both are variable, however, and selection of best species and cultivars is merited.[46,47]

Perennials are desired, especially those that regrow unattended after harvesting (e.g., trees that coppice). The productivity of trees is high, and among herbaceous species the C_4-photosynthetic species are often superior in both land and water use under select conditions.[51-54]

In net energy balance, the energy value per unit weight of biomass is primary; as dry weight, it is nearly invariably 18 kJ g^{-1}. Costs of water removal can be a modest fraction of this value. The energy debits for inputs of chemical fertilizers, herbicides, pesticides, for tractor fuel and irrigation, and for amortized energy of manufacturing farm equipment are generally near 20% of raw biomass energy, in any energy-crop candidates.[46,55,56] These debits are less in nonintensive agriculture.[56] Post-harvest energy costs for transportation can be substantial, and they worsen with increased size of operation. Overall, because fossil-fuel inputs are a fair fraction of energy output, Roller et al.[46] propose that the prospect of cheap raw biomass and expensive fossil fuel to be replaced is illusory.

Between raw biomass input and fuel output lie processing energy losses and energy debits for processing-heat inputs. These are most severe in ethanol production. Numerous authors[4-10] debate the precise energy balance; at best it is marginal. However, some people claim, with some justification, that not all energy inputs should be weighted equally...that solid fuels that are abundant, such as coal, should hardly be debited, if at all, i.e., that only liquid fuel balances matter. (This is only apporpriate for nations rich in such solid fuels.) I have discussed the concept of thermal efficiency (energy balance) on a liquids-only basis recently, for coal liquefaction, in quantitative fashion.[57] Regarding process-heat inputs, gasification of biomass, with or without subsequent conversion to liquid fuels such as methanol, is far more favorable. Median thermal efficiencies near 50% are likely.[58]

A few subtleties remain in evaluating energy value of the final product.[15] Alcohols as motor fuels deserve an octane credit against crude petroleum, because refining petroleum to high-octane gasoline consumes a significant energy fraction. Some people[6,59] claim additional credit is due for raised efficiency in combustion with alcohols (even a similar volumetric consumption between alcohols and gasoline, despite much lower energy per volume in the former), but the claim is dubious.[8] Non-energy byproducts merit some energy credits, also. In ethanolic fermentations, dried distillers' grain has an energy equivalent about equal to the cost of alternatively supplying cattle with other protein-rich crops (perhaps 20% of its combustive value, therefore). However, the market is very saturable, and credits will not persist at high biomass production rates.[15] One last subtlety is that some primary products are non-energy, e.g., jojoba waxes, but they substitute for products derived from petroleum feedstocks. Their energy equivalent is several times (say, three?) their raw energy value, because much processing energy is required to upgrade petroleum feedstocks. They are a quite favorable, perhaps most favorable[60] product of biomass.

INITIAL ASSESSMENT OF FOUR BIOMASS ENERGY TECHNOLOGIES

Definitions: Y_r=yield, raw energy (good crop, not best), in GJ $ha^{-1}yr^{-1}$

W =water use, from <u>managed</u> supplies (see B1, preceding Sec.), in m^3GJ^{-1}

e =net energy ratio, (fuel-equivalent out)/(all energy inputs)

L =land use, in 10^6ha required to produce 10^{18} J yr^{-1}, <u>net</u>

P =power producible, in 10^{18} J yr^{-1}, in specified area, within environmental constraints

<u>A.1 Temperate zone: ethanol from food grains</u>

Y_r= 54 (wheat, kernels only)[46] to 180 (corn, ears + 1/3 residue)[46]

W = 0 (dryland wheat) to 1400 (irrigated corn)[56]

e = -0.5 to +0.5[4-10]; likely 0.1 with very good technology; 0.5 on liquids-only basis with very good technology?

P $\leq$1 in U. S.; limits are erosion tolerance, then water availability--to about $50x10^6$ ha?[1,45-47]

Special impacts: $+CO_2$ in air is likely small; most land to be used has low cover already or has been cleared; gene-pool loss probably small, mostly lost already; water-quality impact depends upon wheat/corn mix.

<u>2. Same, but from cellulosic residues only</u>

Y_r about 1.5 to 2 times larger; most other factors scale down by inverse of this factor. See Larson,[1] for example, for detailed, piecemeal evaluations that are necessary.

<u>3. Temperate zone: methanol from grains and herbaceous crops</u> (via gasification and catalytic reaction of $CO + H_2$)

e = +0.5; all impacts about 1/5 of case (1), and P about 5 or more times larger

<u>B. Jojoba (wax, as energy equivalent); semi-tropical</u>

Y_r = 10? (about 0.5 tonne wax $ha^{-1}yr^{-1}$); W = 0? (dryland);

e = 3 (feedstock credit ratio)x0.7 (extraction debits) = 2; L about 50

P $\leq$0.25 in U. S.; limitation is primarily by area of suitable climate and soil.

Special impact: selectively high loss of arid-area gene-pool!

C. Tropics: ethanol from sugar cane and root crops

Y_r = 250 to 900 (from 50 tonnes $ha^{-1}yr^{-1}$, estimated;[61] lower figure from discounting for low sugar/high cellulose content in non-maturing Amazonian plantings)

e = 0.3?; L = 4

Limitations: in new land clearing, the danger of irreversible destruction of areas; erosion tolerance? (needs study); Power limits? (need study)

Special impacts: irreversible gene-pool loss currently in progress; perhaps significant $+CO_2$ in air.

D. Silviculture for methanol via gasification

Y_r = 200 (pine, temperate zone)[46] to 600? (eucalyptus, tropics)

W about 0?; e = 0.4 (more processing than for herbaceous spp. of case (A3))

L about 4 to 12

Limitations: need much study.

CONCLUSIONS AND FURTHER OBSERVATIONS

(1) Environmental constraints on net power production are strong...presuming that nations do want to preserve agricultural bases (I have some doubts). The prospects are best in tropics, especially relative to demand, but much care is needed to avoid catastrophic environmental destruction.

(2) Preferences: methanol better than ethanol; residues better than total energy crops, in temperate zone.

(3) Erosion-tolerant arable land is quite limited; marginal land gives little hope[15,46] and will likely not favor energy production over food production.

(4) Impacts to watch most closely are permanent productivity losses and gene-pool losses; the latter are historically enormous in the temperate zones and are increasing in the tropics (with little effective concern by temperate-zone nations).[62]

(5) Externalization of environmental costs by producers must be countered; the largest of these costs far exceed the short-term benefits provided. The modern economic panacea, "the marketplace," is part of the problem rather than the solution here, especially in global impacts such as $+CO_2$, in that it rewards externalization and promotes the "tragedy of the commons."

(6) Relative to coal liquefaction[57] as an alternative liquid-fuel source, biomass energy technologies promise to have far larger environmental impacts, and should be preferred only by coal-poor nations of limited power demands. For coal-rich nations, liquid-fuel conservation by task-efficiency increases[63] almost surely deserves first consideration economically and environmentally.

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